Ka-band SAR Interferometry Studies for the SWOT Mission

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SWOT Overview

Mission Science

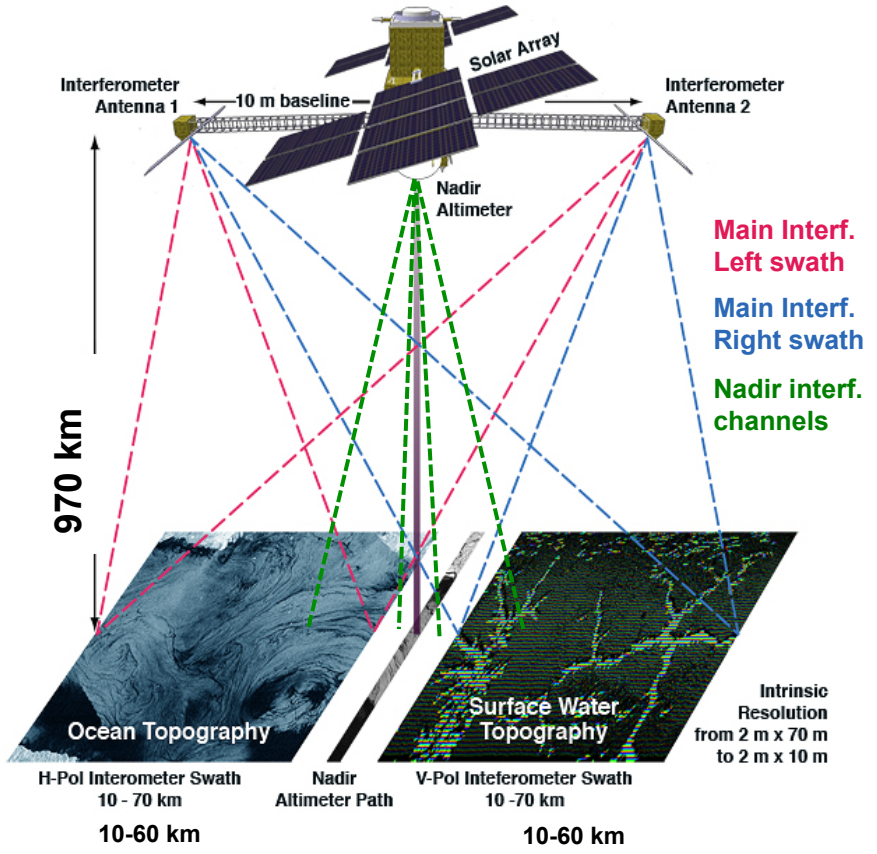
Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and greater.

Hydrology: To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250m)^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (requirement) (50 m goal) (rivers).

- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

Mission Architecture

- Ka-band SAR interferometric (KaRIn) system with two swaths, 50 km each (goal of 60 km)
- Produces heights and co-registered all-weather imagery
- Use conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/Doris/LRA for POD.
- On-board data compression over the ocean (1 km^2 resolution). No land data compression onboard.



- Partnered mission with CNES
- Mission life of 3 years
- 970 km Orbit, 78º Inclination, 22 day repeat
- Flight System: ~1400Kg, ~2.1kW
- Readiness for launch 2019 (TBC)

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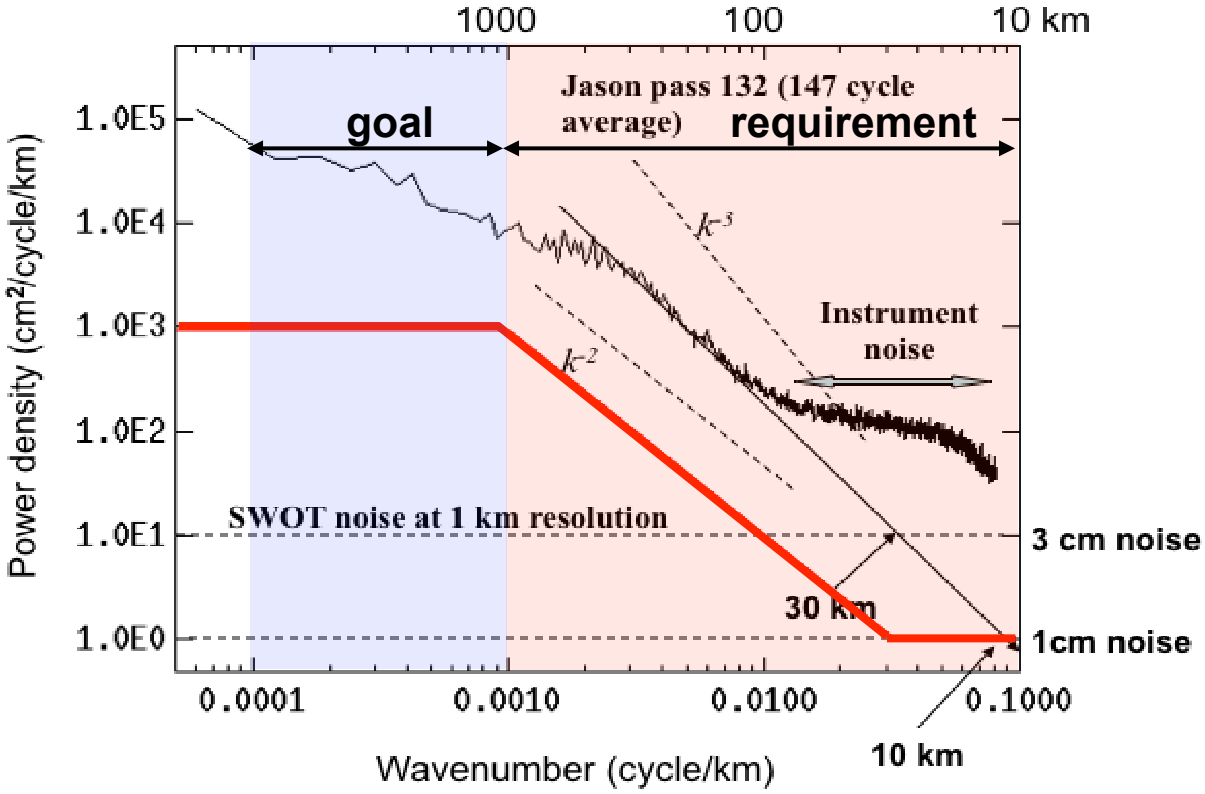
Ocean Measurement Requirements

Ocean SSH error spectral requirement (to resolve signals down to 10 km wavelength) :

2.7.2.a [Requirement] The sea surface height error spectrum in the wavelength range smaller than 1,000 km shall not exceed the spectrum envelope given in the figure and the formula below.

2.7.2.b **[Goal]** The sea surface height error spectrum in the wavelength range between 1,000 km and 10,000 km shall not exceed the spectrum envelope given in the figure and the formula below.



The SSH spectrum is defined such that the SSH error **variance** in the interval $[\lambda_{\min}, \lambda_{\max}]$ is:

$$\left\langle (\delta h)^2 \right\rangle = \int_{1/\lambda_{\max}}^{1/\lambda_{\min}} E(f)\,df$$

And the SSH RMS error is:

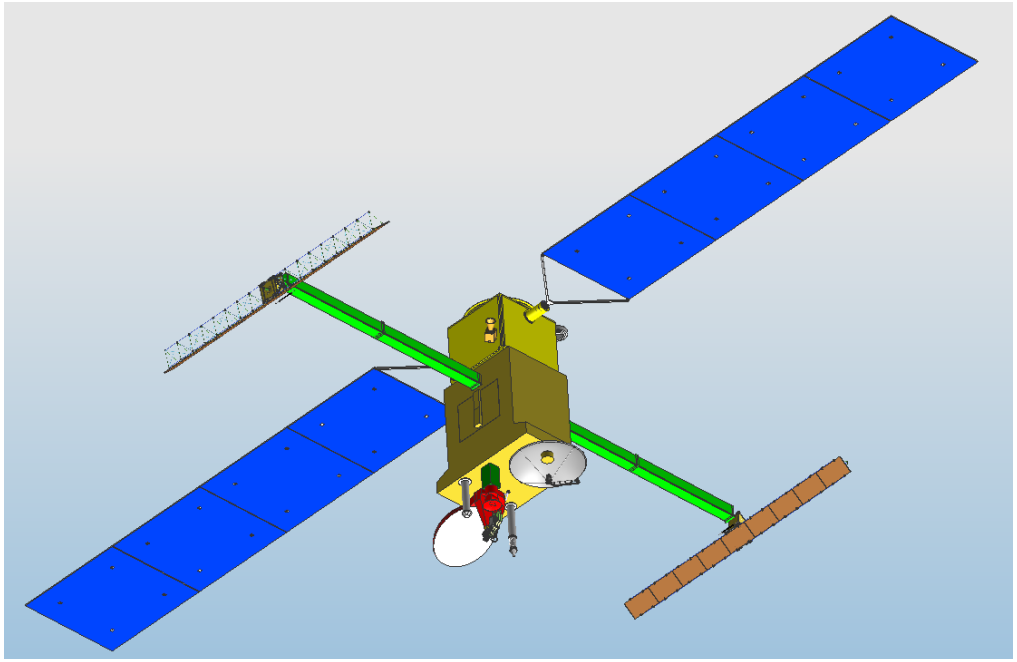
$$\varepsilon_{ssh} = \sqrt{\left\langle (\delta h)^2 \right\rangle} = \sqrt{\int_{1/\lambda_{\max}}^{1/\lambda_{\min}} E(f)\,df}$$

$$E(f) = \begin{cases} 1000 \ \ \mathrm{cm}^2/(cycle/km) & , 1{,}000\ km < \lambda < 10{,}000\ \ km \\ 0.001\ \mathrm{f}^2 \ \ \mathrm{cm}^2/(cycle/km) & , 31.62\ km < \lambda < 1{,}000\ \ km \\ 1 \ \ \mathrm{cm}^2/(cycle/km) & , 1\ km < \lambda < 31.62\ km \end{cases}$$

SWOT The SWOT Mission development challenges

The technology developments for the SWOT Mission addressed in this on-going ESTO Instrument Incubator Program (IIP) are:

- Reflectarray antennas
- On-board Interferometric SAR processor
- High-frequency, un-externally calibrated radiometry



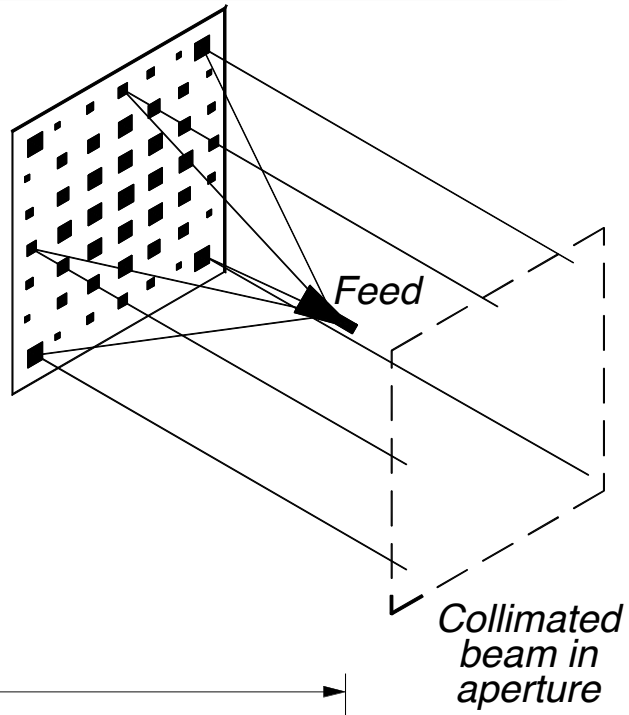
SWOT Antenna Challenges

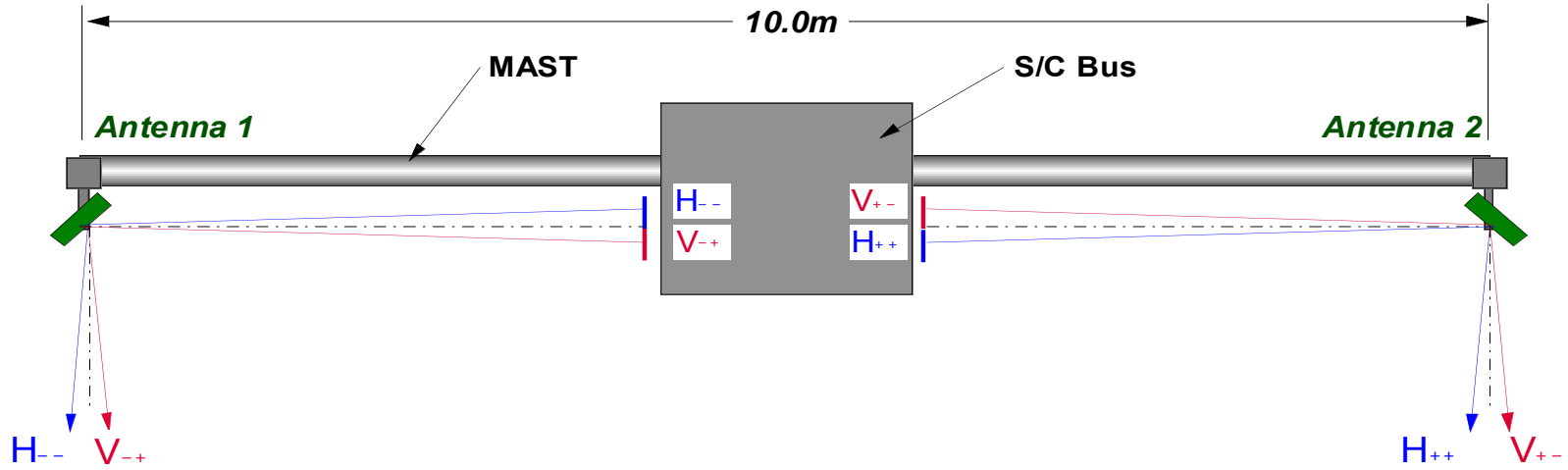
- Long (10m) baseline interferometer
- Requires two large antennas (5 m x 0.3 m) accurately separated by a deployable boom
- Key antenna challenges:
  - Dual channel (scanning) capability:
    - Two beams (two polarizations), one for each swath.
  - Stow the large antenna structure inside the launcher fairing
  - Reduced mass of both antenna and boom (but ensuring stiffness).
  - Minimize transmission line loss from antenna to radar electronics
  - Beam pointing stability (deployment repeatability and on-orbit thermal stability)
  - On-orbit phase, roll and baseline stability between the two sides of the interferometer's antennas
  - Meet RF electrical requirements in on-orbit thermal and vibration environment

SWOT General Microstrip Reflectarray Description

Microstrip reflectarray characteristics

- Consists of an array of radiating elements, such as patches or dipoles mounted on a substrate
- Uses free space transmission of power from feeds to reflector; eliminates need for transmission line
- A parameter of the element is varied, such as size or stub trim length, to control the reflected phase over a 360° cycle
- The elements are varied across the reflectarray surface to create a collimated beam in the aperture





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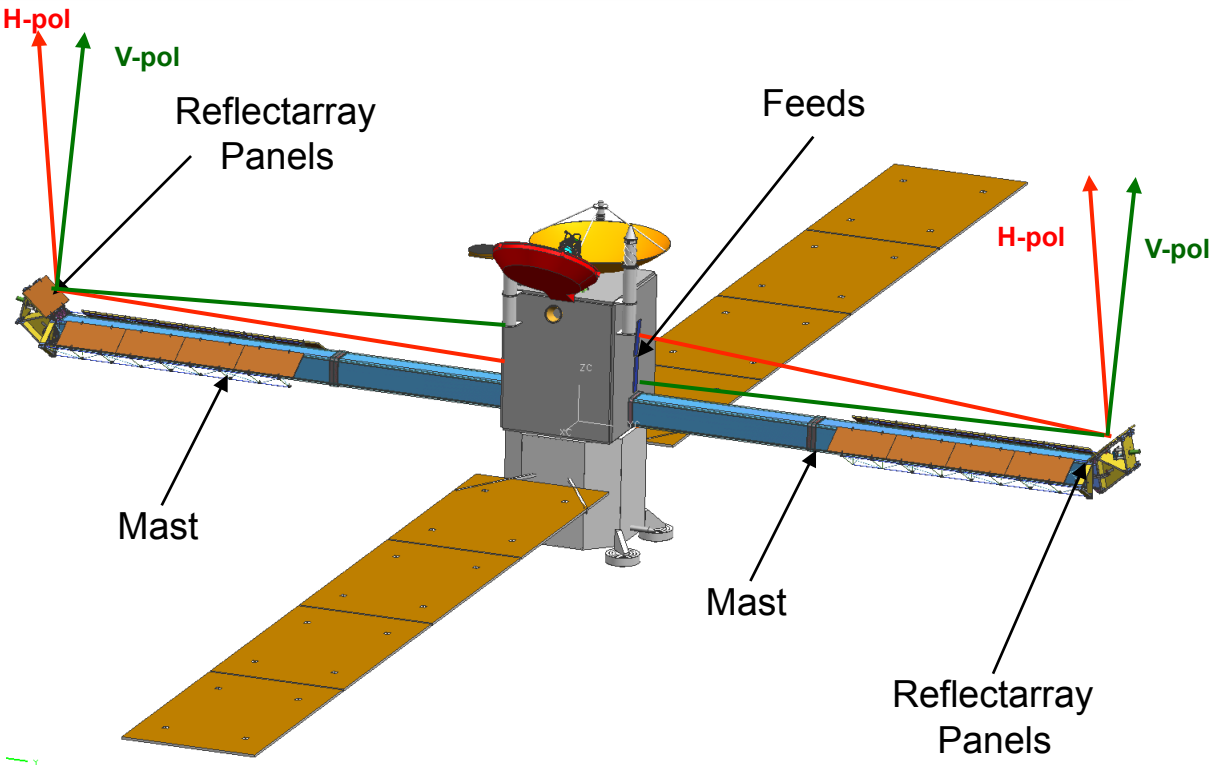
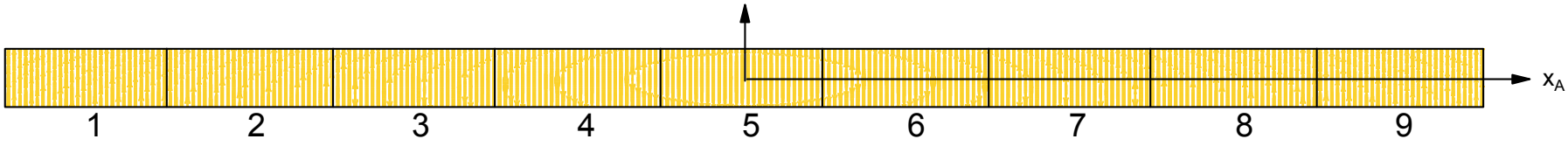
Antenna Technology Approach

Reflectarray antenna technology benefits:

- Dual beam and dual polarization capability
- Flat panels fold compactly
  - provides stowage solution
- Reflectarray panels can provide low mass density
- Free space transmission minimizes loss. No deployable waveguide.





- 9 panels
- Honeycomb sandwich construction
- Square patch elements printed on Rogers RO4003 substrate
  - Full array has over 70,000 reflectarray elements

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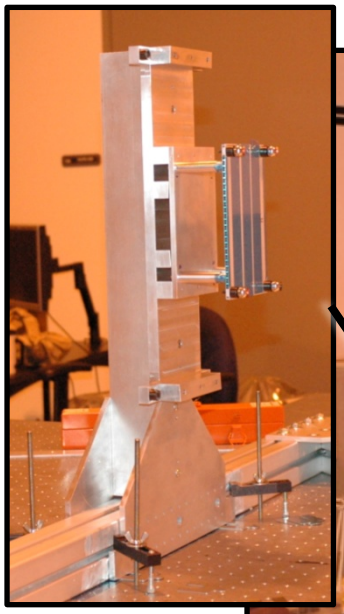
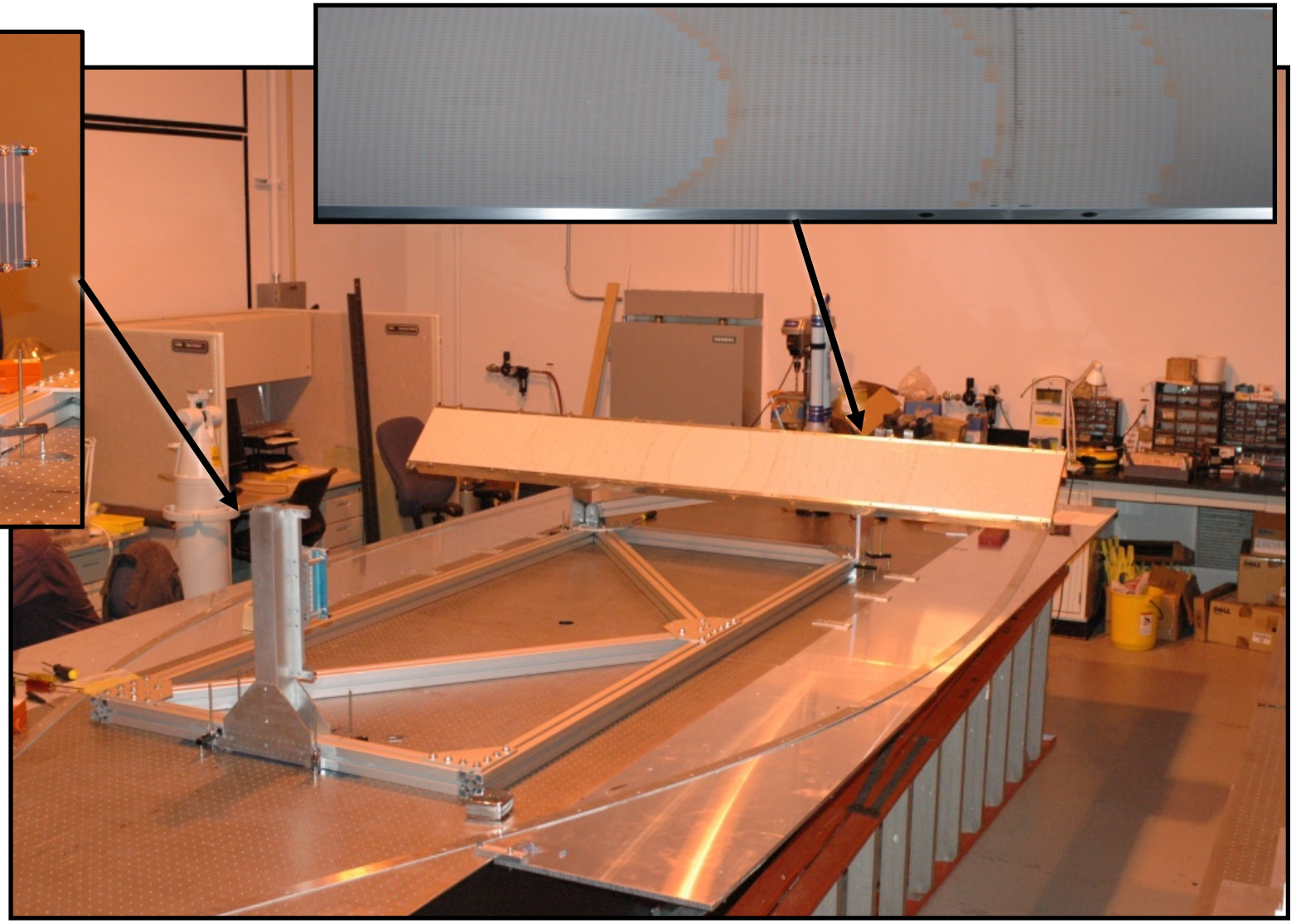
Half-scale feed/reflectarray prototype

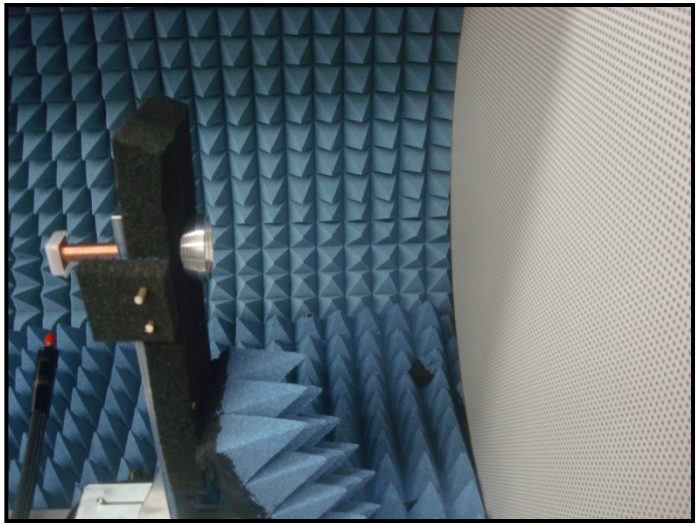


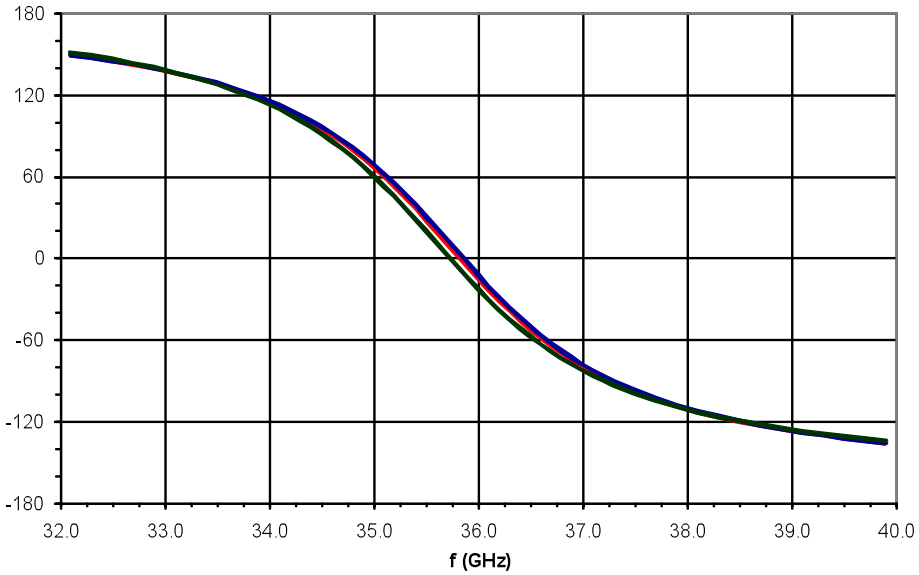
Flatness of ~0.005" on radiating surface

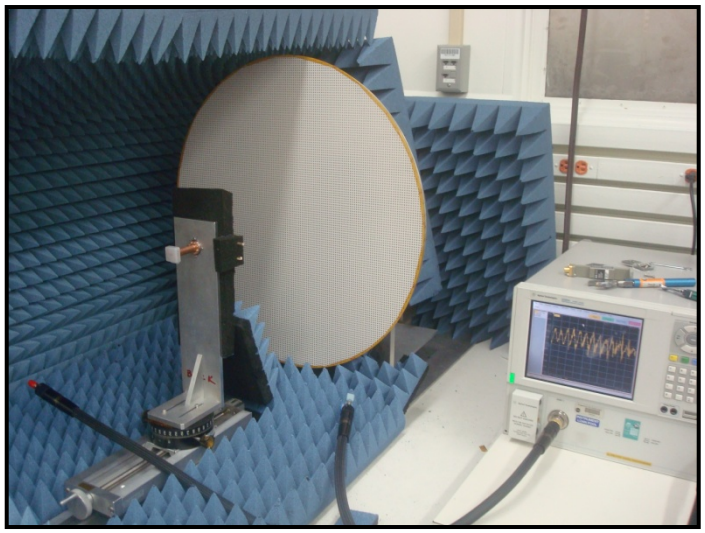


Reflectarray Reflection Measurement

- Reflection measurement of patch resonant frequency
  - Lab Benchtop reflection test
  - Objectives
    - Verify PCB fabrication accuracy
    - Derive effective dielectric constant at Ka-band
    - Estimate patch loss
    - Use in full antenna synthesis





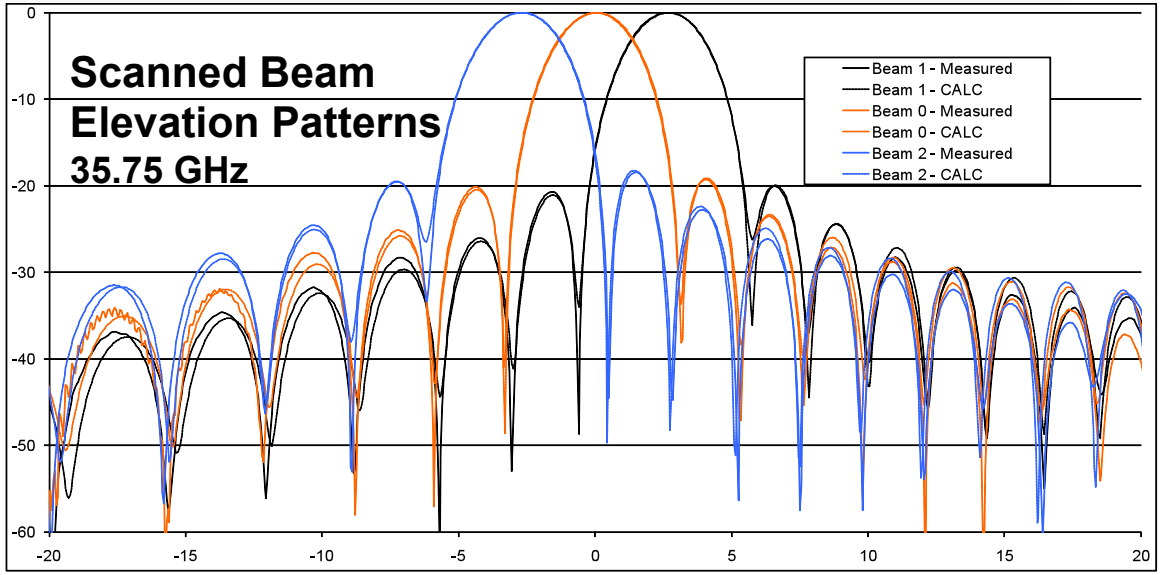


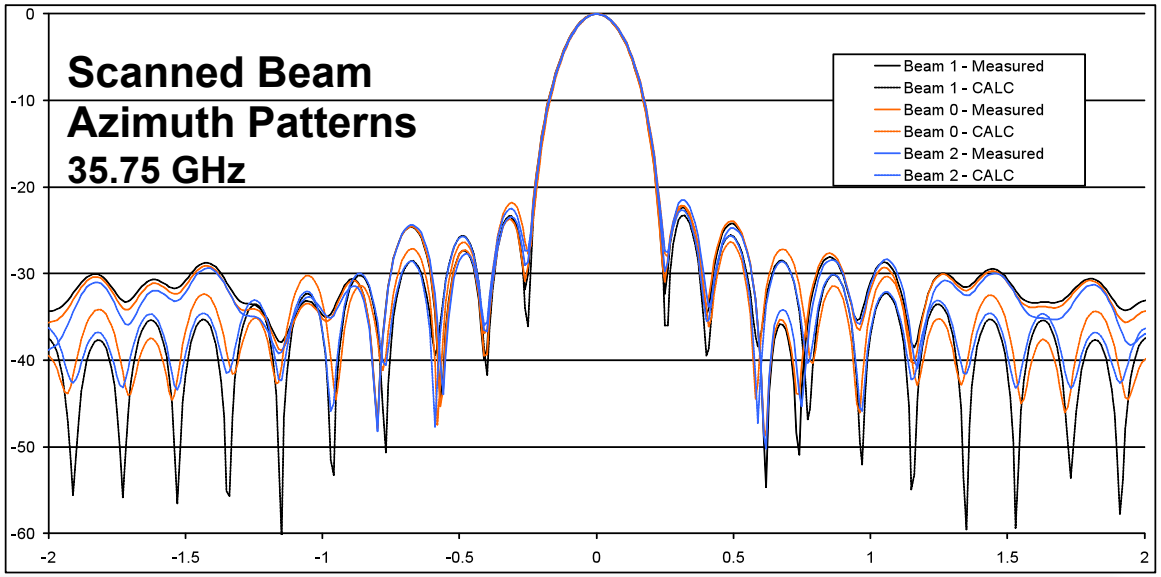
Scanned Beam Patterns

- **ELEVATION PATTERNS**
  - Same feed used for three scan positions
  - No sidelobe beamwidth or sidelobe degradation with scan
  - Measured pattern in good agreement with predicted pattern

- **AZIMUTH PATTERNS**
  - Patterns cut through peak of elevation pattern
  - Azimuth beam matches predicted pattern shape and beamwidth
  - Sidelobes meet requirement but show some deviation from predicted values

- Measurement effort in progress





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On-Board Processor (I)

- *GOAL*: Develop and prototype an FPGA-based on-board processor to minimize the radar's output data rate (~290 Mbps or ~166 Gbytes/orbit for the longest ocean pass).

  The on-board processor will perform interferometric SAR processing and multi-look averaging to decrease the data rate over the oceans before downlink.

- *HERITAGE:* We build on the heritage of WSOA, where a *real-aperture* interferometric processor was developed through NASA's Instrument Incubator Program (IIP) and tested under the NASA OSTM mission funding.

  The higher resolution of SWOT requires an order of magnitude improvement.

- Current status:
  - Completed "Golden" (floating-point) Model, Bit-True Model and VHDL implementation of the algorithm
    - Assessed the end-to-end performance.
  - Developed On-Board Processor HW (board) prototype development.

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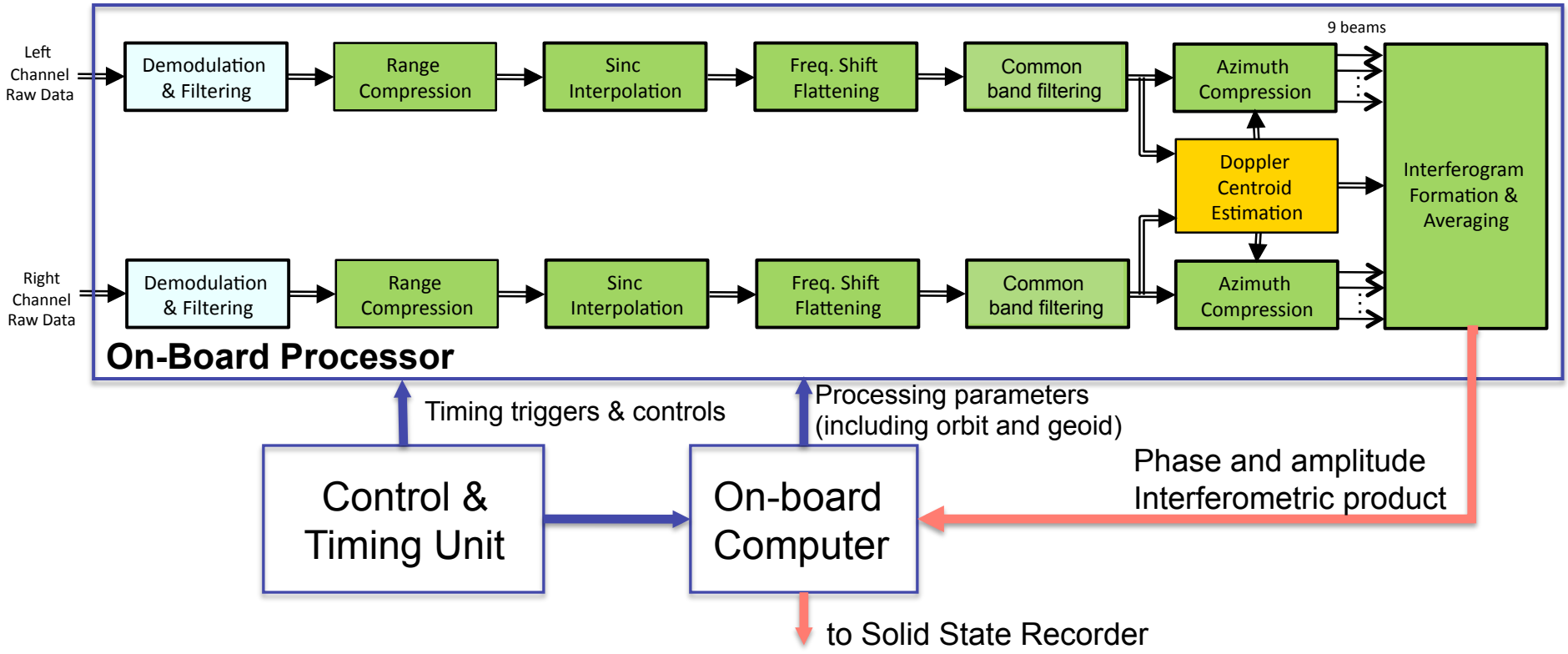
On-Board Processor (II)

Operating parameters:

- 200 MHz signal bandwidth (0.75 m slant range resolution)
- ~ 5 KHz maximum PRF per channel
- 2 x 60 km cross-track swaths
- Single-look ground resolution: 10-70m in range, ~250m in azimuth
- Output resolution: 1x1 km (~200 kbps; a reduction factor of 1,450)
- Height error budget for OBP: 2 mm @ 1x1 km (∞ SNR)

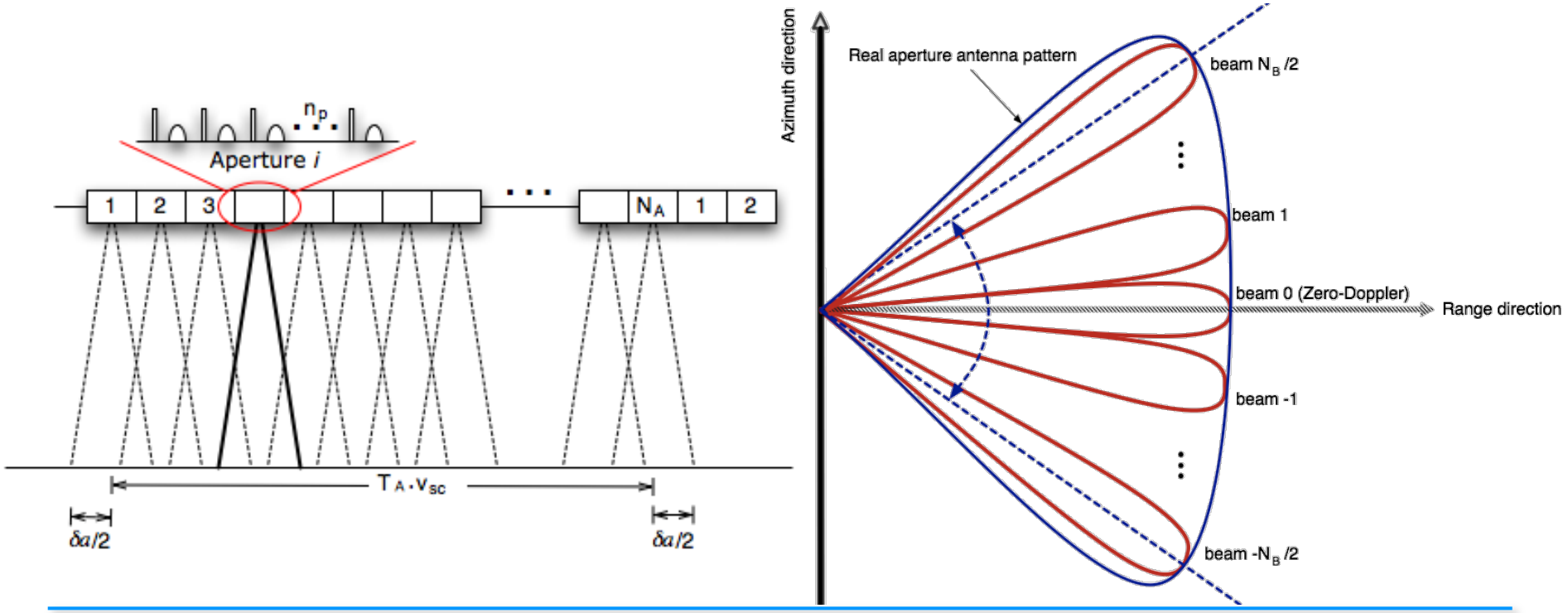


On-Board Processor (III)

The OBP implements Doppler-sharpened, multi-squint SAR processing, primarily to reduce the computational requirements while meeting the low phase error requirements.

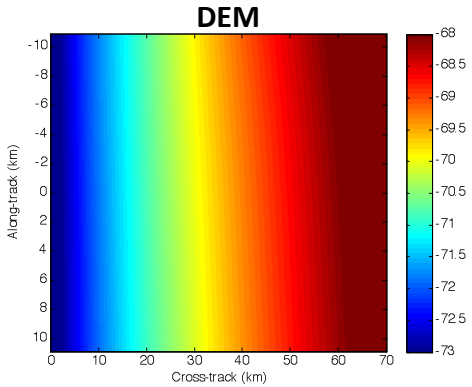
This approach is similar to beam forming, where a number of beams are created within the real aperture azimuth antenna pattern.

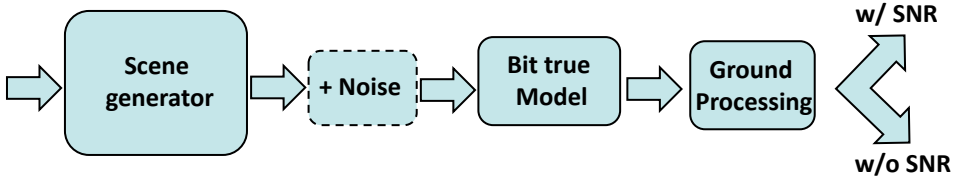
- Each beam uses 9 pulses, for an azimuth resolution of ~250 m.
- An interferogram is formed separately for each beam since they are uncorrelated (averaging can only occur at the interferogram level, during ground processing).

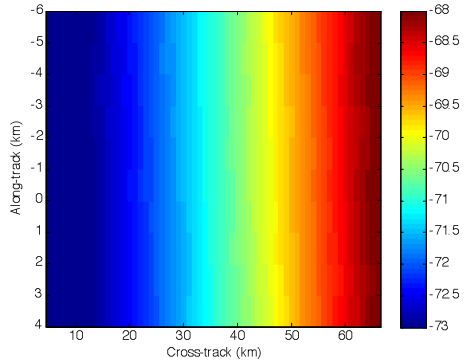


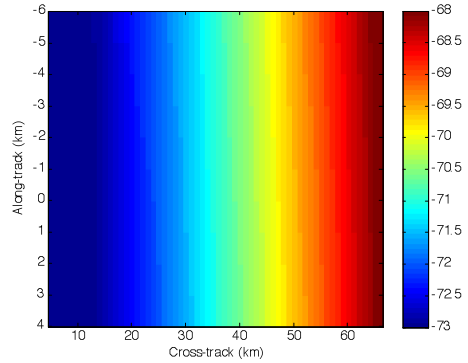
Performance example

10km (at) x 70 km (ct) scene generated including effect of Geoid

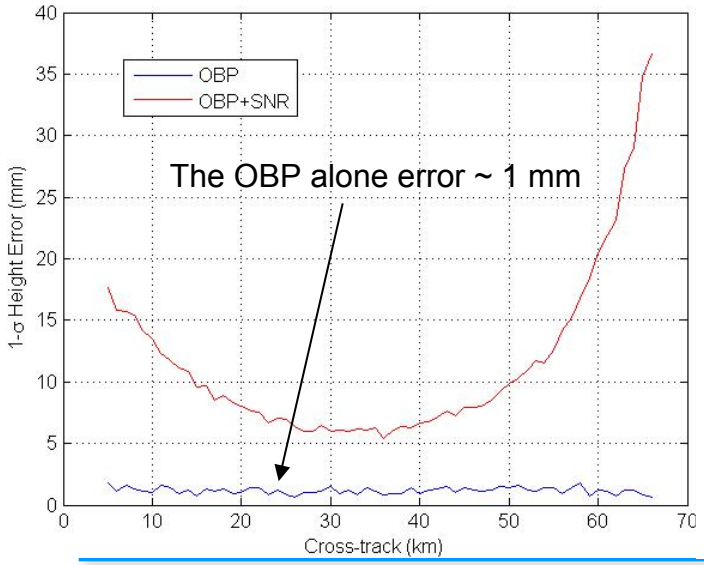


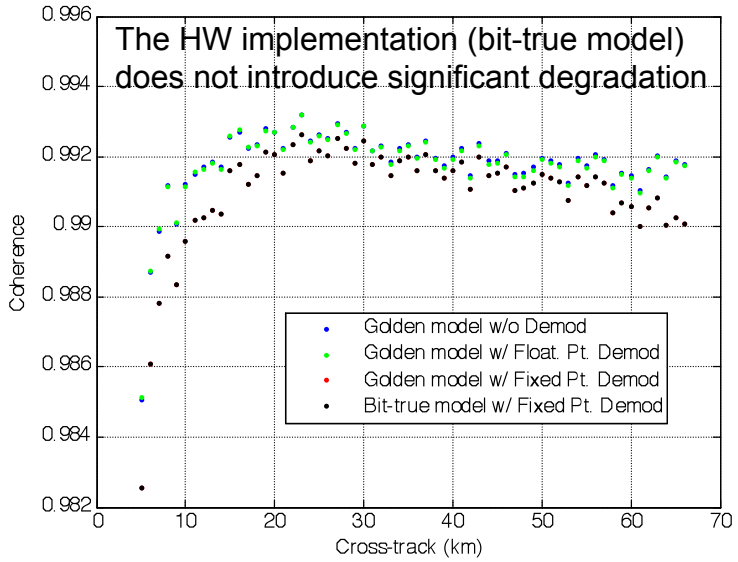






Height error from 10-60km





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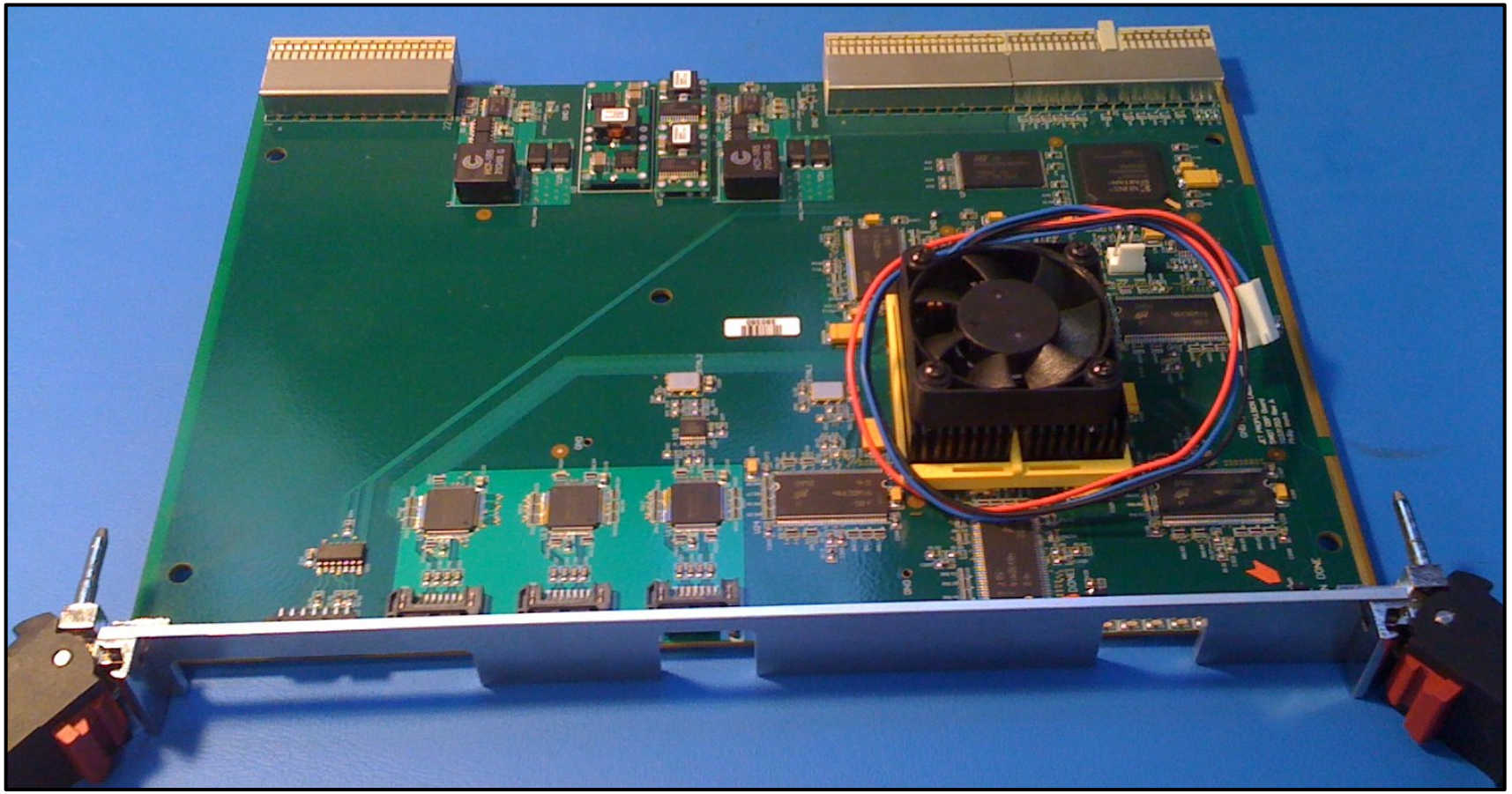
BB OBP Hardware Testing

- Also developed a breadboard FPGA processing board for SWOT
- All interface code developed and tested, and performance demonstration started



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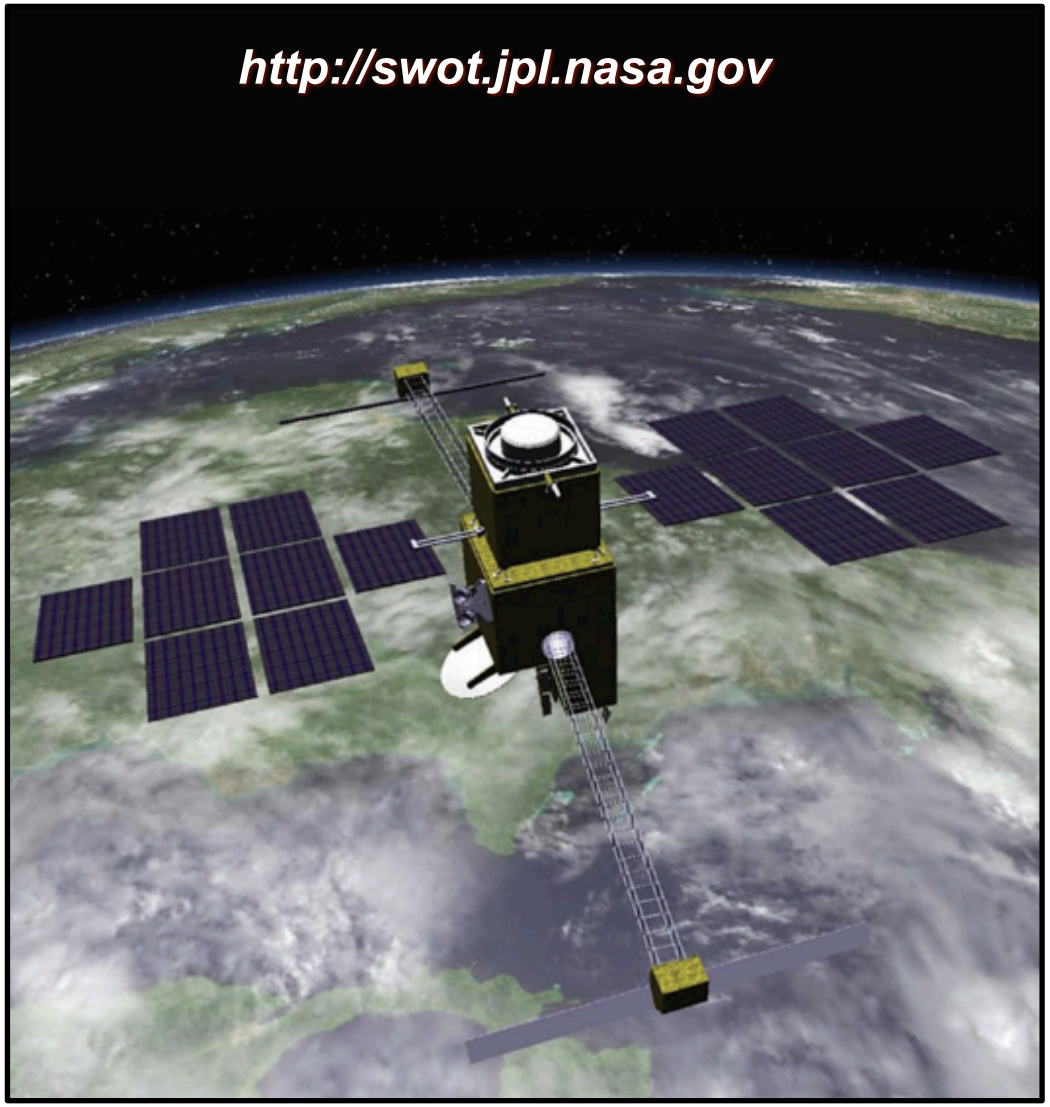
Summary



Currently addressing several key technology developments to reduce mission risk and increase the technology readiness level for implementation in the SWOT Mission.

- Reflectarray antenna
  - BB complete and initial RF measurement performed
  - Full characterization will be completed before end of task
- On-board processor
  - Golden and Bit-true model (VHDL) fully developed
  - BB OBP HW board developed
  - HW integration, testing and performance demonstration will be completed before end of task
- High-frequency, externally un-calibrated radiometry